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Docket No.: NEC 99641
Date: March 14,2000

BOX PATENT APPLICATION
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Dear Sir:

Transmitted herewith for filing is the patent application of:

Inventor: Satoshi Ishizaka and Kazuo Nakamura
For: Magnetic Signal Transmission Line

Enclosed are the following:

[ ] Letter: SUBMISSION OF INCOMPLETE APPLICATION
[X] Specification 11 pages; Claims 3 pages; Abstract 1 page
[X] Declaration and Power of Attorney
[X] sheet(s) of drawings 3 pages
[X] An assignment of the invention to: NEC Corporation
[ ] A verified statement to establish small entity status
[X] A certified copy of Japanese application No. 11-76373, filed March 19, 1999
11-76389 March 19, 1999
[ ] Prior Art Disclosure Statement
[ ] Preliminary Amendment

Priority is hereby claimed under 35 USC 119 by way of Japanese patent application No. 11-76373 filed March 19, 1999.
11-76389 March 19, 1999

Benefit is hereby claimed under Title 35, United States Code 119(e) of United States provisional application No. ________ filed ________.

The filing fee has been calculated as shown below:

		SMALL ENTITY	LARGE ENTITY
BASIC FEE:		$ 345.00	$ 690.00
TOTAL CLAIMS:	16 - 20 = -0-	x 9 =	x 18 = -0-
INDEPENDENT CLAIMS:	2 - 3 = -0-	x 39 =	x 78 = -0-
MULT. DEPEND. CLAIMS:		+130 =	+ 260 = --0-
TOTAL:		$	$ 690.00

[X] A check in the amount of $ 730.00 is enclosed to cover the fees.
[X] ($40.00 Assignment recordal fee is included)

The Commissioner is hereby authorized to charge any additional filing fees required under 37 CFR 1.16 or credit any overpayment to Deposit Account No. 08-1391.

Attorney of Record
Norman P. Soloway, Reg. No. 24,315

CERTIFICATE OF EXPRESS MAILING

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I hereby certify that this paper and the papers listed thereon are being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above, and is addressed to BOX PATENT APPLICATION, Assistant Commissioner of Patents, Washington, D.C. 20231.

Signature of person mailing: Kristine Stevens
Name of person mailing: Kristine Stevens

MAGNETIC SIGNAL TRANSMISSION LINE

BACKGROUND OF THE INVENTION

(a) Field of the Invention

The present invention relates to a magnetic signal transmission line and, more particularly, to a magnetic signal transmission line for transmitting a signal through a one-dimensional array of a plurality of single-magnetization domains.

(b) Description of a Related Art

Metallic interconnects, such as copper and aluminum interconnects, or low-resistance polysilicon interconnects are generally used in an electronic circuit for signal transmission. The transmission rate in the signal transmission by using the metallic interconnects or polysilicon interconnects is restricted by a delay constant (CR constant) of the interconnect, the CR constant being defined by the product of the resistance R by the parasitic capacitance C of the interconnect. The CR constant is currently a primary factor limiting the transmission rate in a smaller-size electronic circuit.

More specifically, signal transmission on the order of several hundreds of giga-hertz requires a conductor having an electric conductivity lower than that of copper which is currently used as a practical low-resistance material.

In addition, a signal transmission line having a width as small as 100 nm or less is not achieved by a current technology for the integrated circuit. This limits the degree of integration in the semiconductor integrated circuit.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a new signal transmission line capable of being fabricated to have a smaller width as small as 100 nm or less and having a transmission rate which is higher compared to that achieved by the current technology.

It is another object of the present invention to provide a method for signal transmission by using a magnetic signal transmission line

The present invention provides a magnetic signal transmission line including a substrate having a main surface, and a plurality of single-magnetization domains arranged in a one-dimensional array on the main surface, each of the single-magnetization domains having a magnetization, whereby a signal is transferred along the one-dimensional array by a change of the magnetization.

The magnetic signal transmission line of the present invention is free from the problem encountered in the conventional signal transmission line wherein the signal transmission rate is limited by the CR constant, and has an advantage that the width of

the signal transmission line can be made as small as 100 nm or less.

The above and other objects, features and advantages of the present invention will be more apparent from the following description, referring to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a partial top plan view of a magnetic signal transmission line according to a first embodiment of the present invention.

Fig. 2 is a longitudinal sectional view of the magnetic signal transmission line of Fig. 1.

Fig. 3 is a partial top plan view of a magnetic signal transmission line according to a second embodiment of the present invention.

Fig. 4 is a longitudinal sectional view of the magnetic signal transmission line of Fig. 3.

Fig. 5 is a partial top plan view of a magnetic signal transmission line according to a third embodiment of the present invention.

Fig. 6 is a longitudinal sectional view of the magnetic signal transmission line of Fig. 5.

Fig. 7 is a graph for showing exemplified signal transmission characteristics of the magnetic signal transmission line, with a parameter being the ratio of the anisotropic energy to the interactive energy between magnetic dipoles.

PREFERRED EMBODIMENTS OF THE INVENTION

In the magnetic signal transmission line of the present invention, each single-magnetization domain (or magnetic domain) preferably has a spontaneous magnetization. A magnetic signal transmission line made of a ferromagnetic material has such spontaneous magnetization. A preferable distance between the adjacent single-magnetization domains is such that the interactive energy acting between magnetic dipoles in both the adjacent single-magnetization domains in terms of the absolute temperature is higher than the operational ambient temperature of the magnetic signal transmission line. It is preferable that the direction of the easy axis of the single-magnetization domain reside in parallel with the main surface of the substrate, and in a direction along or perpendicular to the direction of the one-dimensional array of the single-magnetization domains.

It is also preferable that the dimension of each single-magnetization domain perpendicular to the substrate, i.e., the height be smaller than both the dimension along the one-dimensional array, i.e., length, and the dimension perpendicular to both the aforementioned dimensions, i.e., width of the single-magnetization domain. It is preferable that the width of the single-magnetization domain have a width equal to or larger than the length thereof.

In the description to follow, the length, width and height of

the single-magnetization domains are defined by the dimension thereof along the direction of the array, the dimension thereof perpendicular to the length and parallel to the main surface of the substrate, and the dimension thereof perpendicular to the main surface, respectively.

Each single-magnetization domain may be separated from one another on the substrate with a space disposed between adjacent single-magnetization domains, or may be distributed as a part of a single continuous unit constituting the signal transmission line. It is preferable that the single-magnetization domains be periodically arranged.

The basic structure of the magnetic signal transmission line of the present invention includes a one-dimensional array of ferromagnetic bodies each having a minute structure formed on a non-magnetic substrate. The typical structure of the magnetic signal transmission line is as follows.

Each minute ferromagnetic body has width, length and height which are smaller than the thickness of the magnetic wall of a bulk of the ferromagnetic material used therefor so that each minute ferromagnetic body forms a single-magnetization domain and has a uniform spontaneous magnetization in the magnetic domain.

Each minute ferromagnetic body has a flat shape wherein the height is smaller than the length and the width, and has an easy plane for magnetization parallel to the substrate surface, whereby

the spontaneous magnetization can be rotated within the easy plane.

The arrangement of the minute ferromagnetic bodies is such that the distance between adjacent ferromagnetic bodies is as small as possible and typically equivalent to the dimensions of the ferromagnetic body. The distance between adjacent single-magnetization domains is such that an interactive force acts between magnetic dipoles in the adjacent ferromagnetic bodies and that the interactive energy between the adjacent ferromagnetic bodies in terms of the absolute temperature is higher than the operational ambient temperature, typically a room temperature.

Selection of different values between the width and the length of the minute ferromagnetic body provides an anisotropic energy wherein a difference occurs in the magnetic energy between a spontaneous magnetization aligned with the direction of the width of the single-magnetization domain and a spontaneous magnetization aligned with the direction of the length of the single-magnetization domain. The selection of dimensions is such that the width is equal to or significantly larger than the length so that the anisotropic energy of each single-magnetization domain resides between 0% to 120% of the interactive energy acting between magnetic dipoles in the adjacent minute ferromagnetic bodies.

The magnetization of minute magnetic body moves in co-operation with adjacent minute magnetic body when suitable values are selected for the interactive energy between magnetic dipoles and the anisotropic energy of the single-magnetization

domain. Thus, the direction of the magnetization in the minute ferromagnetic bodies or the change thereof can be transferred along the one-dimensional array to achieve a signal transmission using the magnetic signal transmission line.

Now, the present invention is more specifically described with reference to accompanying drawings, wherein similar constituent elements are designated by similar or related reference numerals.

Referring to Figs. 1 and 2, a magnetic signal transmission line according to a first embodiment of the present invention includes a silicon substrate 11, and a one-dimensional array of magnetic dots 10 formed on the main surface of the silicon substrate. The array includes about 10,000 magnetic dots (minute ferromagnetic bodies) 10 in this embodiment. The magnetic dots 10 are made of iron and formed by the steps of forming a resist film on the silicon substrate, exposing the resist film for patterning using an electron beam exposure technique, sputtering iron onto the silicon substrate by using the resist film as a mask, and removing the resist film from the silicon substrate.

Each magnetic dot 10 is of a column shape having a diameter of 20 nm and a height of 10 nm. The distance between adjacent two of the magnetic dots 10 is 10 nm. Since the thickness of the magnetic wall of a bulk of iron is about 30 nm, the magnetic dot 10 having those dimensions, smaller than 30 nm, has a single-magnetization domain structure. The interactive energy acting between the magnetic dipoles in adjacent magnetic dots 10 is

obtained from the distance between the magnetic dots 10, the dot dimensions and the saturation magnetization of iron, and is calculated at about 10,000K in terms of the absolute temperature. This allows the magnetic dots 10 to operate at a room temperature. In this embodiment, the equality between the length and the width of the magnetic dot provides no in-plane anisotropy therein.

Referring to Figs. 3 and 4, a magnetic signal transmission line according to a second embodiment of the present invention is similar to the first embodiment except for the configuration of the magnetic dots 10A. Specifically, the one-dimensional array of magnetic dots 10A is formed by etching an iron wire having a width of 30 nm. The array includes 10,000 magnetic dots 10A having a length of 20 nm, a width of 30 nm and a height of 10 nm, whereby the magnetic dots 10A are arranged with a pitch of 30 nm and a distance of 10 nm between adjacent magnetic dots 10A. The interactive energy acting between the magnetic dipoles in the adjacent magnetic dots 20 is obtained by the distance between dots, dot dimensions and the saturation magnetization of iron, and calculated at 10,000K in terms of the absolute temperature. The calculated interactive energy allows the magnetic dots to operate at a room temperature. The larger value for the width compared to the length as measured parallel to the substrate surface provides an in-plane anisotropy, wherein the magnetization has an easy axis in the direction perpendicular to the direction of the array.

Referring to Figs. 5 and 6, a magnetic signal transmission

line according to a third embodiment of the present invention is similar to the first embodiment except for the distance between the magnetic dots 10B. The distance is selected at 5 nm in the present embodiment, which allows the magnetic dots 10B to have an interactive energy of 20,000K in terms of the absolute temperature between magnetic dipoles in the adjacent dots. In Fig. 5, the spontaneous magnetization of each magnetic dot 10B is depicted by an arrow, and is aligned with the direction of the array except for the location designated by numeral 12.

In the signal transmission line according to the present embodiment, the magnetic moment of each magnetic dot assumes a minimum due to the interactive energy when the magnetization is aligned with the direction of the array. If the magnetic signal transmission line is subjected to rotation of the magnetization of one or some of the magnetic dots, as shown at the location 12, the rotation of the magnetization can be transferred as a solitary wave at a high speed in the direction of the array. The transmission rate of the solitary wave can be calculated from the distance between the dots, the height of the dot and the saturation magnetization of iron. The calculated rate is 100m/s in the third embodiment.

The transmission rate 100 m/s itself is not very large compared to the transmission rate in a conventional signal line. However, considering that the magnet signal line has a very small length due to its high-density-integration capability, and that a number of solitary waves can be transmitted at a transmission end

in sequence without arrival thereof at a reception end, the calculated transmission rate 100 m/s is satisfactory. The solitary wave can be applied with a magnetic field by a magnetic head at the transmission end, and read from a magnetic field by another magnetic head at the reception end.

Referring to Fig. 7, there is shown the signal transmission rate in the magnetic signal transmission line of the present invention. The signal transmission rate is shown by the travel distance of a solitary wave plotted with time (nano-second) and with a parameter of "K", which is the ratio of the anisotropic energy of the magnetic domain to the interactive energy acting between magnetic dipoles in the adjacent magnetic domains. The parameter "K" may be selected at a desired value by selecting the ratio of the major axis to the minor axis in a magnetic dot of an ellipse. For the parameter "K" which is between 0 and 1.2, the solitary wave can be transferred substantially at a constant rate due to the interactive energy acting between dipoles in adjacent single-magnetization domains.

Since the above embodiments are described only for examples, the present invention is not limited to the above embodiments and various modifications or alterations can be easily made therefrom by those skilled in the art without departing from the scope of the present invention. For example, in the above embodiment, the easy axis of the single-magnetization domain is aligned with the direction of the array. However, the easy axis may

be perpendicular to the direction of the array in the present invention.

WHAT IS CLAIMED IS:

1. A magnetic signal transmission line comprising a substrate having a main surface, and a plurality of single-magnetization domains arranged in a one-dimensional array on said main surface, each of said single-magnetization domains having a magnetization, whereby a signal is transferred along said one-dimensional array by a change of said magnetization.

2. The magnetic signal transmission line as defined in claim 1, wherein said single-magnetization domain is formed in a magnetic material having a spontaneous magnetization.

3. The magnetic signal transmission line as defined in claim 2, wherein said magnetic material is a ferromagnetic substance.

4. The magnetic signal transmission line as defined in claim 1, wherein an interactive energy acting between dipoles in adjacent two of said single-magnetization domains in terms of the absolute temperature is larger than an operational ambient temperature.

5. The magnetic signal transmission line as defined in claim 1, wherein each of said single-magnetization domains has an easy axis which is parallel to said main surface.

6. The magnetic signal transmission line as defined in claim 5, wherein said easy axis is parallel to a direction of said one-dimensional array.

7. The magnetic signal transmission line as defined in claim 5, wherein said easy axis is perpendicular to a direction of said one-dimensional array.

8. The magnetic signal transmission line as defined in claim 1, wherein each of said single-magnetization domains has a height smaller than both a width and a length thereof.

9. The magnetic signal transmission line as defined in claim 1, wherein each of said single-magnetization domains has a width equal to or larger than a length thereof.

10. The magnetic signal transmission line as defined in claim 1, wherein each of said single-magnetization domains is separated from an adjacent one of said single-magnetization domains with a space disposed therebetween.

11. The magnetic signal transmission line as defined in claim 1, wherein each of said single-magnetization domains is distributed as a part of a continuous unit of the magnetic signal transmission line.

12. The magnetic signal transmission line as defined in claim 1, wherein said single-magnetization domains are arranged periodically in said one-dimensional array.

13. The magnetic signal transmission line as defined in claim 1, wherein each of said single-magnetization domains has an anisotropic energy which resides between zero and 120% of interactive energy acting between dipoles in adjacent two of said single-magnetization domains.

14. A method for transmitting a signal by using a one-dimensional array of a plurality of single-magnetization domains, said method comprising the steps of applying a magnetic field to at least one of the single-magnetization domains to cause a change of magnetization therein, and detecting a magnetization of another of said single-magnetization domains.

15. The method as defined in claim 14, wherein said change of magnetization includes a change of direction of a spontaneous magnetization.

16. The method as defined in claim 14, wherein said change of magnetization is transferred as a solitary wave.

ABSTRACT OF THE DISCLOSURE

A magnetic signal transmission line includes a one-dimensional array of a plurality of single-magnetization domains each formed in a ferromagnetic body. The anisotropic energy of the single-magnetization domains is zero to 120% of the interactive energy acting between dipoles in adjacent single-magnetization domains. The single-magnetization domains are formed by sputtering iron onto a silicon substrate by using a mask.

FIG. 1

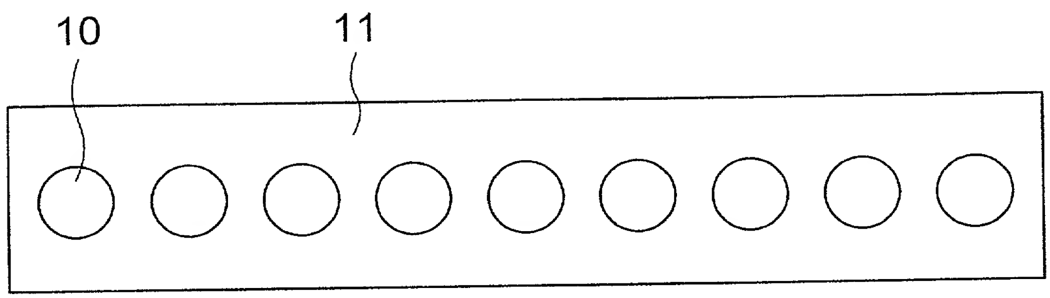


FIG. 2

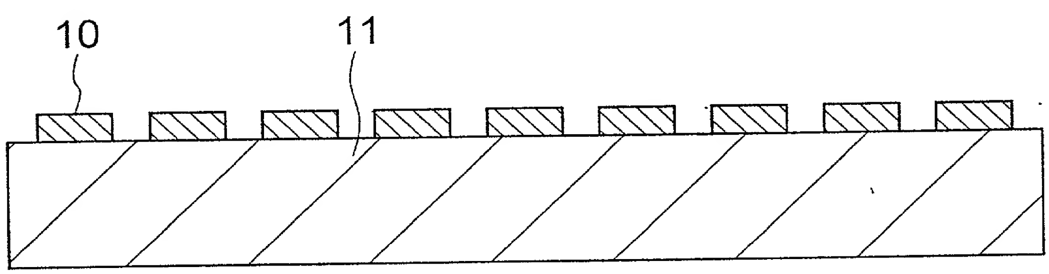


FIG. 3

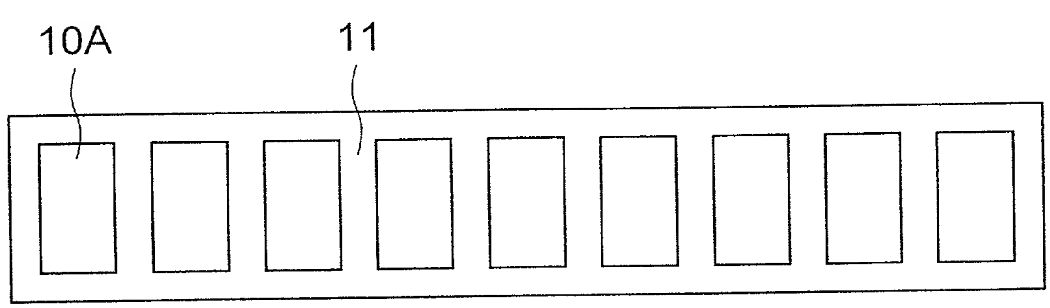


FIG. 4

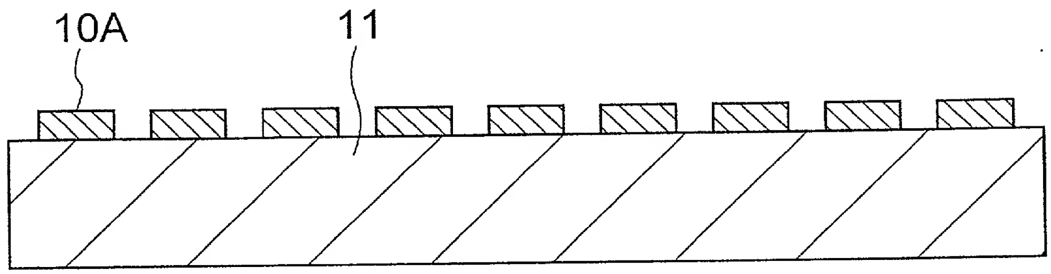


FIG. 5

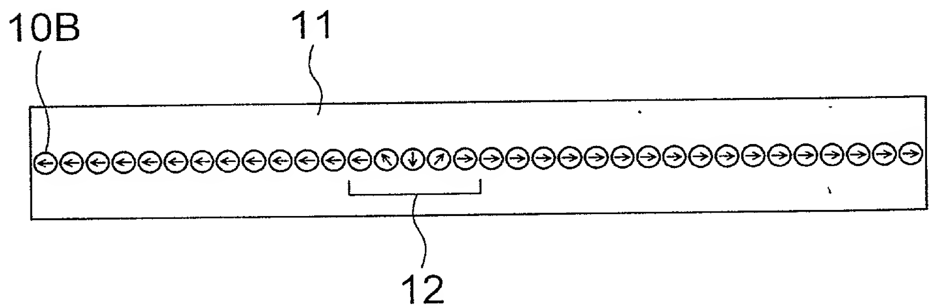


FIG. 6

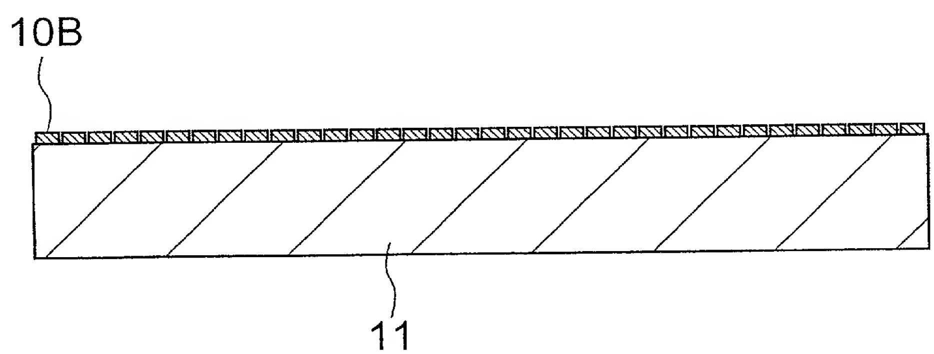
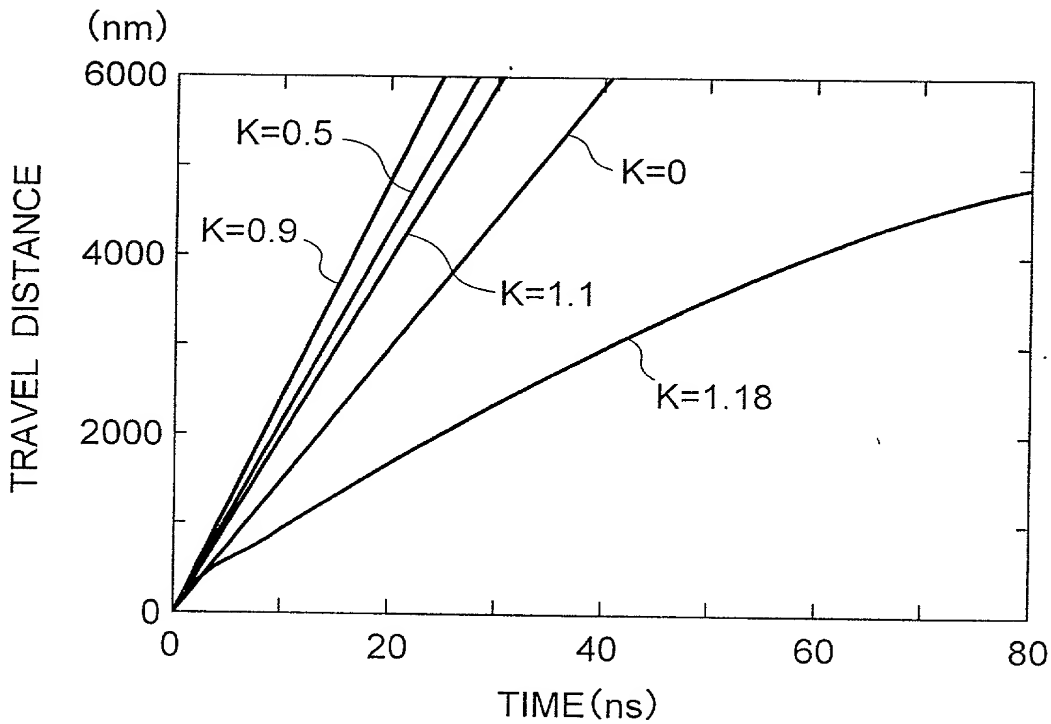


FIG. 7


(nm)
6000
4000
2000
0
TRAVEL DISTANCE
K=0.5
K=0.9
K=0
K=1.1
K=1.18
0
20
40
60
80
TIME (ns)

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

Attorney Docket No: NEC 99641

First Named Inventor: Ishizaka et al

Complete if known: Serial No: ______ Filing Date: March 14, 2000

Group Art Unit: ______ Examiner: ______

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled MAGNETIC SIGNAL TRANSMISSION LINE, the specification of which: ☒ is attached hereto **or** ☐ was filed on ______ as application Serial No. ______, and was amended on ______ (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, S. 1.56(a).

I hereby claim foreign priority benefits under 35 U.S.C. 119(a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below any foreign application for patent or inventor's certificate or of any PCT international application having a filing date before that of the application on which priority is claimed:

Prior Foreign Application(s):

(Number)	(Country)	(Month/Day/Year Filed)	Priority Claimed	Certified Copy Attached
11-76373	Japan	03/19/1999	☒ Yes ☐ No	☒ Yes ☐ No
11-76389	Japan	03/19/1999	☒ Yes ☐ No	☒ Yes ☐ No

I hereby claim the benefit under 35 U.S.C. 119(e) of any United States provisional application(s) listed below:

Application No: ______ Filing Date: ______

I hereby claim the benefit under 35 U.S.C. 120 of any United States application(s), or 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C 112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application:

US Parent Application or PCT Parent Number	Parent Filing Date	Parent Patent Number (if applicable)

And I hereby appoint HAYES, SOLOWAY, HENNESSEY, GROSSMAN & HAGE, P.C., a firm composed of Oliver W. Hayes, Reg. No. 15,867; Norman P. Soloway, Reg. No. 24,315; William 0. Hennessey, Reg. No. 32,032; Susan H. Hage, Reg. No. 29,646; Steven J. Grossman, Reg. No. 35,001; ~~Christopher K. Gagne, Reg. No. 36,142~~; and Edmund Paul Pfleger, Reg. No. 41,252, or any of them, of 175 Canal Street, Manchester, New Hampshire 03101 (Telephone: 603-668-1400) my attorneys with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent Office connected therewith.

Please direct all future correspondence in connection with this application to the attention of **Norman P. Soloway** HAYES, SOLOWAY, HENNESSEY, GROSSMAN & HAGE, P.C., 175 Canal Street, Manchester, New Hampshire 03101 (Telephone: 603-668-1400).

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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